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AUTHOR(S): K. I. Thomassen

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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TECHNOLOGY PROBLEMS IN THETA PINCH REACTORS

Keith I. Thomassen

LOS ALAMOS SCEINTIFIC LABORATORY
P. O. Box 1663
Los Alamos, New Mexico 87545

An earlier assessment of the first complete conceptual engineering design of the Reference Theta Pinch Reactor (RTPR) identified problem areas in the design involving plasma stability, neutral gas cooling, implosion circuitry, compression energy supplies, materials for the blanket and first wall, and tritium handling. New solutions to some of these problems are described, and a new RTPR operating point has been chosen which greatly alleviates many of the problems.

INTRODUCTION

Among the three principal magnetic confinement schemes for fusion reactors the theta pinch is unique in being a short-pulsed, batch-burn reactor. This leads to advantages over mirrors and tokamaks but also presents unique technology problems. These problems were first identified in the RTPR design,[1] the first complete theta pinch fusion reactor design. The plant layout is shown in Fig. 1. Based on that design, an assessment of these major problems was published.[2]

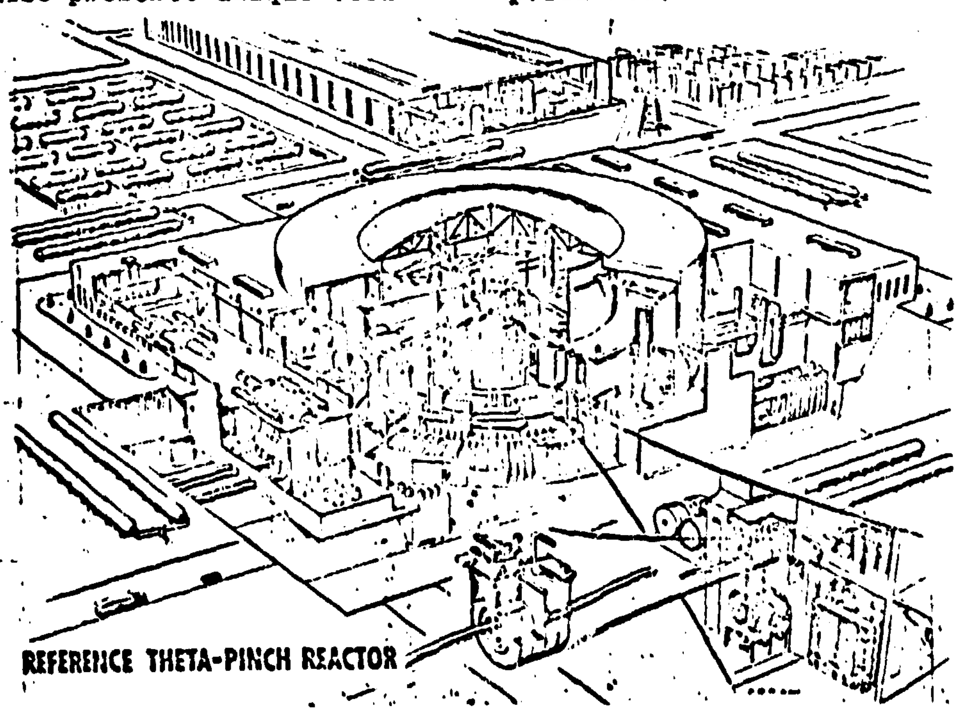

FIGURE 1. The Reference Theta Pinch Reactor - plant layout.

That assessment identified problems in the areas of plasma stability, neutral gas cooling, implosion heating circuitry, pulsed compression energy supplies, materials and radiation damage (composite first wall and also blanket materials), and tritium handling. The last of these is a problem common to all fusion devices, so this paper will discuss progress toward solutions to the remaining problems which are unique to the theta pinch.

PLASMA STABILITY

The operating point described in the RTPR design envisions a plasma first wall radius of 50 cm and a plasma radius which varies from 50 cm at the time of initial heating down to 11 cm at peak compression 30 ms later. At these small radii the plasma is unstable to m = 1 long wavelength modes since the stabilizing influence of induced wall current is absent. Either the plasma radius must be kept larger (~15 cm) or the plasma must be stabilized by feedback techniques currently in use[3] on Scyllac. Since the plasma compression needed to reach ignition limits the choice of operating points we have chosen to employ feedback control in the most recent

TABLE 1. Comparison of Old and New RTPR Operating Points

SYMBOL	DEFINITION (UNITS)	OLD VALUE	NEW VALUE
E_θ	Implosion-heating electric field (kV/cm)	2.0	0.7
B_{SH}	Implosion-heating magnetic field (T)	1.4	0.88
P_A	D-T filling pressure (mTorr)	17	7
B_O	Maximum compression field (T)	11	7
τ_R	Compression-field rise time (ms)	30	30
τ_{FT}	Compression-field flat-top time (ms)	70	400
W_N	Fusion neutron yield (MJ/m)	93.11	86.73
W_{BO}	Total ETS energy (MJ/m)	286	97
A	Aspect ratio	112	100
b	First-wall radius (m)	0.5	0.5
η_{ETS}	ETS transfer efficiency	0.98	0.95
Q_E	Engineering Q-value W_{ET}/W_C	6.5	5.7
ϵ	Recirculating power fraction	0.16	0.18
$\Delta T_{w(s)}$	First-wall surface temperature rise (K)	310	150
ΔT_w	Maximum temperature decrease across firstwall (K)	250	30

reactor design.[4] Table 1 summarizes key parameters in the old and new designs.

The feedback system required for the RTPR presents a technical challenge, and can also adversely affect the energy balance. However, recent results[5] show that if reasonable constraints are imposed on the line density (particles/meter of torus) and the amplitude of the $\ell = 1$ helical equilibrium field, the feedback power can be kept below 1% of the net output power.

The second stability constraint involves higher order ($m \geq 2$) modes which are stabilized by finite Larmor radius effects.[6] These constraints were not imposed on the original design, but indeed are observed in the new design. The criterion is that the ratio of ion Larmor radius to plasma radius exceed a constant which involves machine design parameters. This constraint imposes rather restrictive limits on the choice of operating points, but by appropriate design choices they can be satisfied.

NEUTRAL GAS COOLING

A neutral gas layer is introduced into the torus near the end of the burn cycle for purposes of adding insulation between the plasma and the first wall material. By choosing the appropriate gas density ($\sim 10^{14}$ cm^{-3}) the heat is removed sufficiently slowly (~ 1 s) as to protect the wall. Early calculations by Oliphant[7] established the heat transfer rates in steady state, and later transient calculations[8] addressed the problems of setting up this neutral gas blanket.

More recent calculations by Oliphant and Gryczkowski[9] have improved on the numerical codes for handling the transient problem, and first wall fluxes and the energy spectrum of incident particles can be calculated. These calculations include charge exchange and ionization by electrons and protons on both atoms and molecules. In addition the Franck-Condon process of dissociation of ionized molecules is included, and second generation (charge exchanged) neutrals are followed. The plasma and neutral density and temperature profiles are evolved in the process.

These codes are in the last stages of development and only early results are available. The output generated by these codes is used in a heat transfer calculation of first wall energy deposition and temperature rise. These results indicate that the plasma edge temperatures are substantially reduced in the early phases of the interactions, limiting the charge-exchanged neutral insult to the wall. Nonetheless, damage to the first wall during the setting-up processes is possible and the operating point chosen for the reactor must avoid any such damage by judicious choices of the available parameters. While it appears now that this can be done further work is in progress and a continuing assessment of the problem must be made.

IMPLOSION CIRCUITRY

One of the most critical areas of design involves the implosion heating system for imparting the initial 1-2 keV temperature to the plasma. The old design required an electric field on the plasma of 2 kV/cm, or a back emf of 650 kV around the plasma circumference. This implies very high circuit voltages and requires good dielectric strength of first wall insulators in the presence of degradation by thermal stresses or radiation.

The circuit voltage depends on the materials and geometry of the partial turn (Marshall) coil[10] used to generate the azimuthal fields. In particular, the dielectric strength of the coil material determines its thickness and therefore its internal inductance. The internal inductance and lead-in inductance determine how much additional circuit voltage must be supplied to provide the necessary plasma voltage. Typically, half the voltage is lost in internal and lead-in impedance, and half is applied to the step-up transformer (partial turn coil) to provide plasma voltage. The 2-m long module used to construct the core of the toroidal reactor is shown in Fig. 2, and gives the relative locations of the Marshall coil, compression coil, and blanket.

At present, there is no complete, self-consistent system design. Instead, attempts to reduce the overall voltage level by the choice of operating point have been made. The recent design has E = 0.7 kV/cm or 220 kV back emf. By optimum use of the partial turn coil this could lead to circuit voltages below 100 kV, and by balancing the system to ground this may be split into 50 kV capacitor units. This reduced field strength is allowed in the new design be-

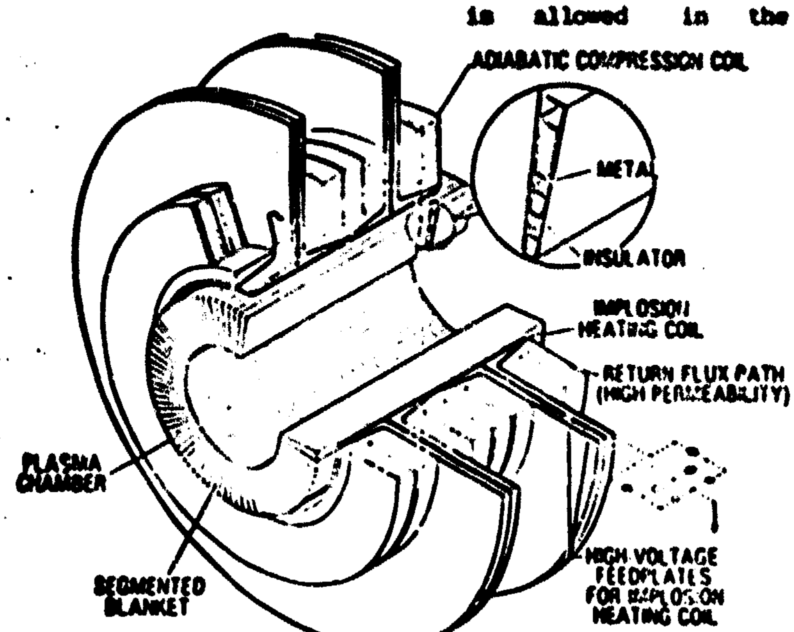

FIGURE 2. One of the two-meter long, linked modules used to construct the torus.

cause more of the plasma energy is now provided by slow adiabatic compression, which in turn is permitted since the highly compressed plasma is now feedback controlled.

COMPRESSION SYSTEM

The RTPR requires 63 GJ of energy delivered in 30 ms to provide the compressional magnetic field of 11 T. The supply must hold the field for 70 ms, and recover 95% of the energy in the 30 ms return. A nested set of 3 superconducting storage coils was used in the old design, so arranged that the two center quadrature coils could be rotated, torque-free, to deliver the energy. While the scheme was capable of 98% efficiency, the projected production costs of 5-6 ¢/J were high, and the technology was unusual and required considerable development.

More recently, fast-discharging homopolar machines, acting as electrodynamic capacitors, were proposed.[11] These machines are more similar in their technologies to existing rotating apparatus. Further, they appear capable of 95% efficiencies in the RTPR cycle at a cost 0.7 ¢/J. A set of 50 of the machines, storing 1.3 GJ each have been proposed for the RTPR application,[12] and an extensive engineering design of the machine has been reported.[13] Figure 3 shows the 8 thin-drum rotors connected in series to provide 11 kV at 12.25 MA in each unit. Superconducting Nb_3Sn coils give an average radial field of 2.2 T through each rotor. By spinning each drum at a peripheral speed of 277 m/s, each 8-pack stores the 1.3 GJ.

In optimizing the RTPR design the compression field has been lowered to 7T, thereby reducing the energy storage by $(7/11)^2$. The new operating point therefore calls for only 20 units, with an attendent reduction of the number of high power interrupting switches. Since the switching problem is also quite demanding, the new design will have

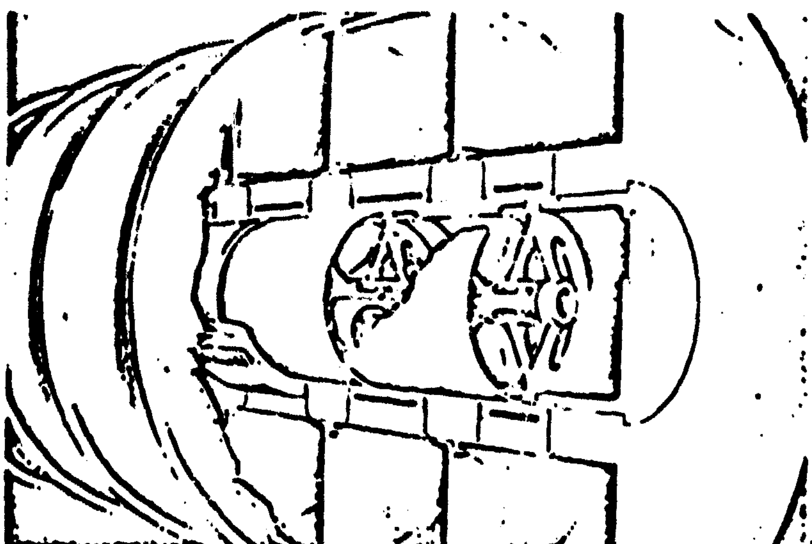

FIGURE 3: An isometric view of an 8-rotor homopolar machine for driving the RTPR compression coils.

a higher reliability by this reduction. Also, the reactor Q is now much less sensitive to the homopolar efficiency, and a Q = 1 break-even point occurs at 63% efficiency as seen in Fig. 4. Engineering details on the new system have yet to be given.

MATERIALS AND RADIATION DAMAGE

Perhaps the most critical design problem in the theta pinch reactor involves the first wall materials. The first wall is the inner surface of a slotted, annular blanket inside the implosion and compression coils as in Fig. 2. These radial slots pass the axial flux, inducing voltage across each slot and at the tip where the slots open into the plasma chamber. Each wedge of the blanket is therefore coated with insulating material which must maintain its adiabatic properties for a reasonable blanket life.

Since present theta pinches admit flux through only 1, 2, or sometimes 4 slots, the field strengths are an order of magnitude higher in present experiments than those anticipated in a 100 slot reactor blanket. Dielectric strength is consequently easy to achieve, but the environment in the reactor is much more severe than in present machines. Perhaps the most significant problems arise from the thermal loading, which results from temperature excursions of 300°K above a base temperature of 800°K in the old design.

Considerable progress has been made both in reducing the thermal excursions and in reducing the stresses for a given temperature rise. This is done by altering the materials, wall thickness, configuration, or operating point. Using the old operating point and associated thermal wall loading several

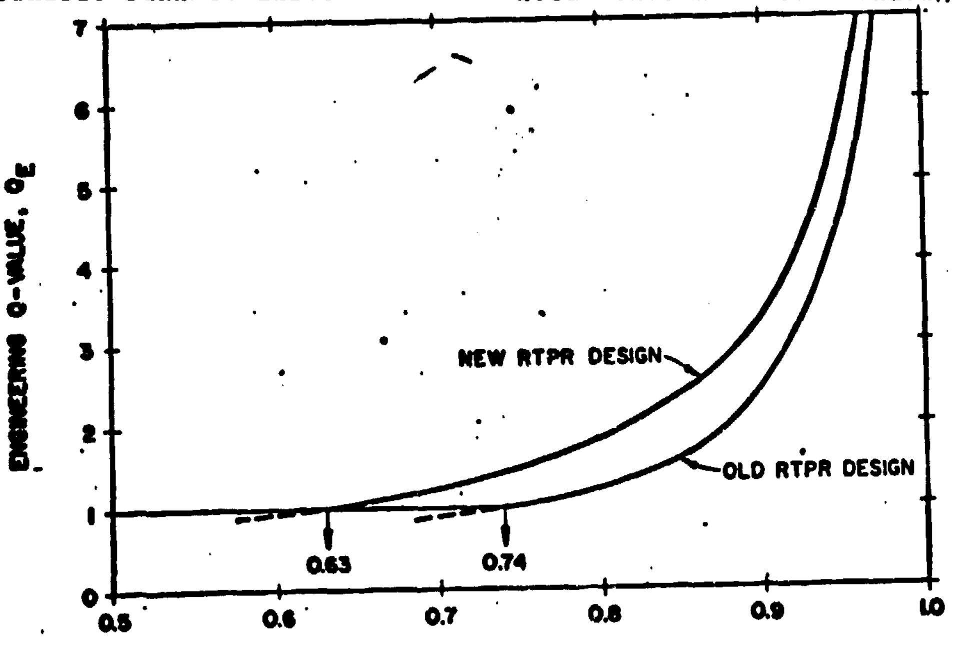

FIGURE 4. Influence on reactor Q of the efficiency η_{ETS} of the Energy Transfer System (ETS).

new schemes were proposed[14] (thinner walls, graded ceramics, bumper protected walls, all ceramic walls, etc), and an analysis to show the reduced stresses was performed.[15] These new designs are shown in Fig. 5. Such an analysis will be done with the new operating point, and significant improvements can be expected.

In addition to the first-wall problem there are questions involving blanket designs and material choices. Considerable effort is being expended to improve the engineering design of the blanket structure, and a design which eliminates most of the welds required in the old design has been developed[16] and is shown in Fig. 6. Also, the materials used in the design are now being chosen so as to eliminate the graphite moderator by adding a thin BeO layer. The entire blanket has also been thinned, improving the reactor Q and lowering the stored magnetic energy even further.

SUMMARY

The major problems in the RTPR design have been discussed, and improvements in these areas have been described. Plasma stability is now ensured in the reactor by adding a feedback control system of some complexity, but the energy balance is not affected. The neutral gas cooling questions are now being addressed with much improved codes, and preliminary results are encouraging. Further effort is required and is underway.

A new design point has been chosen which substantially reduces the

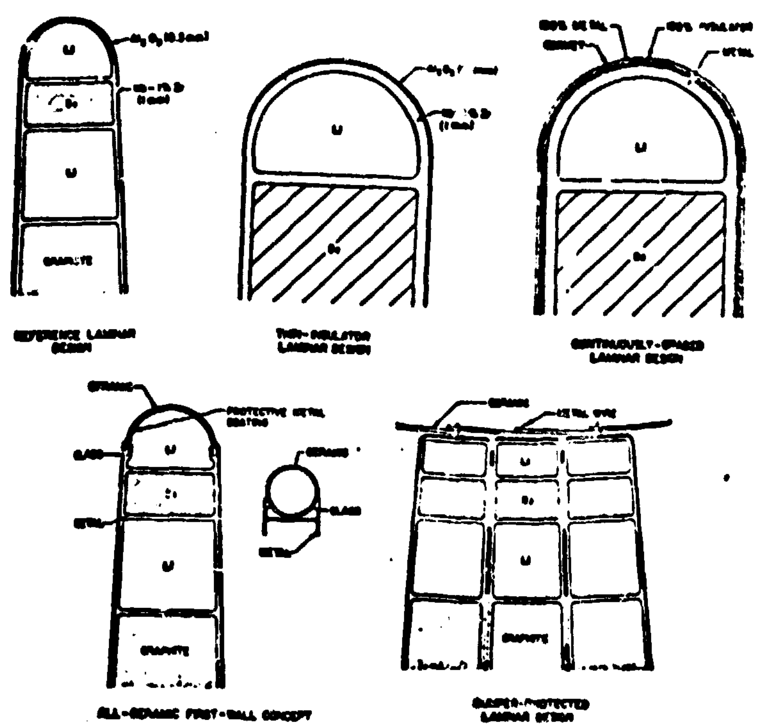

FIGURE 5. New first-wall designs for RTPR.

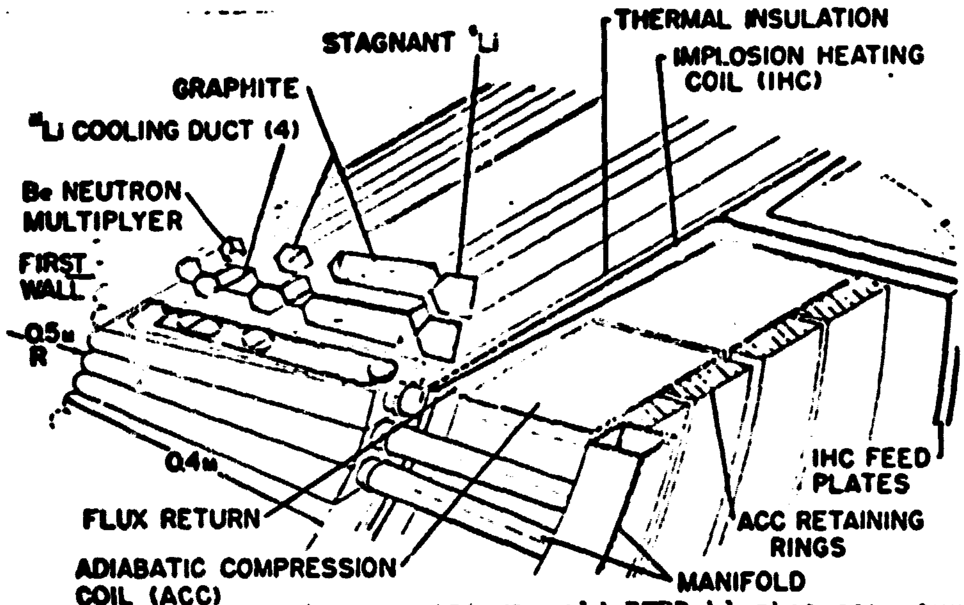

FIGURE 6. A new, minimum-weld RTPR blanket structure.

voltage levels in the implosion circuitry, and also reduces the electric field strengths on the first wall insulator by a factor of 3. This operating point also reduces the stored compression energy by a factor of 2.5, hence the capital cost of that system by 2.5. The thermonuclear output is unchanged.

Finally, new materials choices and configurations have led to improvements in the blanket and first wall designs, and the thermal insult to the first wall has been greatly reduced by the new design point.

It is of paramount importance to note that the major improvements in the new RTPR come from a more nearly optimized operating point than was used in the old RTPR design. This influence of the "plasma engineering" aspects of the reactor design is and will continue to be one of the most important influences on reactor technology for some time.

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